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14. ABSTRACT

Interest in periodic cellular metals has been driven by the structural and thermal management application potential of cellular metal sandwich structures. The research conducted in this program has led to the development of lattice structures which can be configured in the form of various core topologies of sandwich panels with high specific stiffness and strengths amenable for use in multifunctional applications (e.g. thermal dissipation, ballistic resistance). The applications of these lattice structures have been paced by two synergistic developments: the emergence of a micromechanics based approach for topology design and, scalable methods for the affordable manufacture of optimal lattices from high performance engineering materials including metal matrix composites and carbon fiber reinforced polymer systems. New applications of sandwich structures with lattice cores were realized by extending the topology designs to new cellular architectures such as those based on hollow truss assembly configurations and hierarchical structures.

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Final Report

Ultralight Metallic Panels with Textile Cores Designed for Blast Mitigation and Load Retention / Topologically Structured Materials: Blast & Multifunctional Implementations

Grant Number: N00014-01-1-1051

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EXECUTIVE SUMMARY

The research conducted in this program has led to the development of lattice structures which can be configured in the form of various core topologies of sandwich panels with high specific stiffness and strengths. They are of particular interest because of their many potential multifunctional applications.

The applications of these lattice structures have been paced by two synergistic developments: the emergence of a micromechanics based approach for topology design and, scalable methods for the affordable manufacture of optimal lattices from high performance engineering materials. A micromechanics-based design approach was developed as part of this program. In this approach, the (material property and lattice geometry dependent) modes of failure of a lattice structure have been identified for specified loading conditions and optimal configurations identified by manipulating the topology and parent material properties to find situations where failure occurs simultaneously by two or three modes. Fabrication efforts have focused upon approaches for making these best performing topologies from different materials systems. Panels with tetrahedral truss, pyramidal lattice, hollow truss cores were made by these methods in stainless steel and aluminum, experimentally tested and analyzed, the findings of which are documented in a series of papers which appear in the appendices.

Higher stiffness and strength and lighter weight structures were realized by extending the lattice fabrication and topology design approach to high temperature metal (titanium) matrix composites and carbon fiber reinforced polymer systems which are described below.

Technical Objectives

Interest in periodic cellular structures has been driven by structural and thermal management applications of cellular metals. Previous work on a separate Office of Naval Research (ONR) funded program showed at least a 300% increase in structural performance in lattice based structures over stochastic foam sandwich panel analogues of similar relative density. A number of routes to manufacture metallic lattice materials were developed in the original program. These include investment casting to manufacture an Octet-truss type structure, laser cutting and folding to manufacture "Kagome" type and pyramidal lattice materials and a slotting technique to manufacture the triangular and square-honeycomb sandwich cores. New applications of sandwich structures with lattice cores can be realized by extending the topology designs to new cellular architectures such as those based on hollow truss assembly configurations and hierarchical structures. The materials used for fabrication of these structures can be extended from steel and aluminum alloys to high performance materials such as metal matrix composites and Carbon Fiber reinforced polymer systems. The motivation of composite structures is driven by the need to seek materials that fill a void in the high strength-low density material space. The potential multi-functional applications will be explored by case studies with filled or coated lattice materials. Multifunctional benefit for sandwich structures can potentially be accrued by the filling of the empty space within the core with ceramics and polymers for blast mitigation and increased ballistic resistance.

Technical Approach

Titanium matrix composite lattices.

To create high performance, sub-millimeter scale lattice structures, small scale truss components made from advanced materials are needed. Ti-6Al-4V coated SiC (SCS-6) monofilament (240 μm diameter), Fig. 1, was proposed as a new candidate truss material for such lattice structures. Because the SiC monofilament is brittle, fabrication processes are then limited to those that do not involve bending and because Ti-6Al-4V is capable of being diffusion bonded, collinear lattices with square, Fig. 2(a), and diamond topologies, Fig. 2(b), were therefore chosen. A manufacturing method for creating a sandwich panel with collinear TMC truss core and Ti-6Al-4V face sheets was developed and improved. Compressive and shear behaviors of these lattices were investigated at ambient temperature.
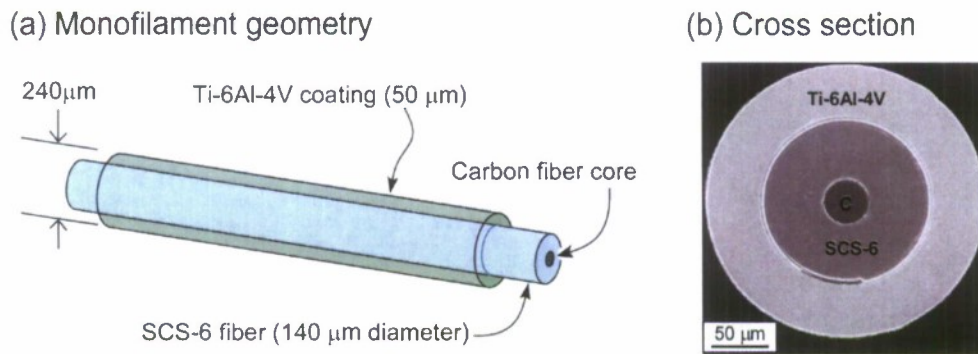
(a) Monofilament geometry   (b) Cross section

Fig.1 (a) Schematic and (b) cross-sectional micrograph of a Ti-6Al-4V coated SCS-6 SiC monofilament (35% fiber volume fraction).

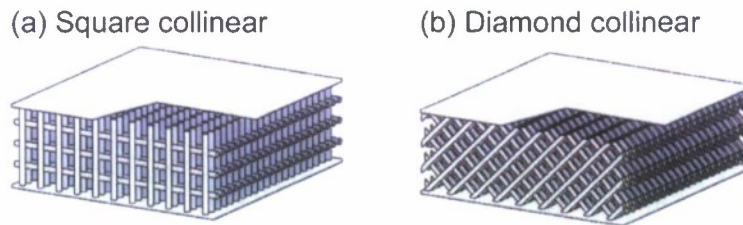### (a) Square collinear   (b) Diamond collinear

Fig. 2 Sandwich panel structures with (a) square collinear and (b) diamond collinear core topologies.

Carbon Fiber Reinforced Polymer lattices.

Several methods for constructing pyramidal CFRP structures have been investigated as shown in Fig. 3. Fibrous composites are highly anisotropic with their best material properties found in the direction along the fiber axis. Due to the difficulty in creating shaped carbon fiber composites, pre-fabricated materials were used to form the trusses and epoxy bonded to the face-sheet at the node. Unidirectional trusses are desirable due to the fact they utilize 100% of the available fiber in the load bearing direction along the truss axis however node design is critical in order to attain the maximum strength of the truss. In both unidirectional truss designs shown in Fig. 3, the panel underwent premature node failure due to the truss being stronger than the node. In order to attain the maximum performance from such structures, the node must be more robust.
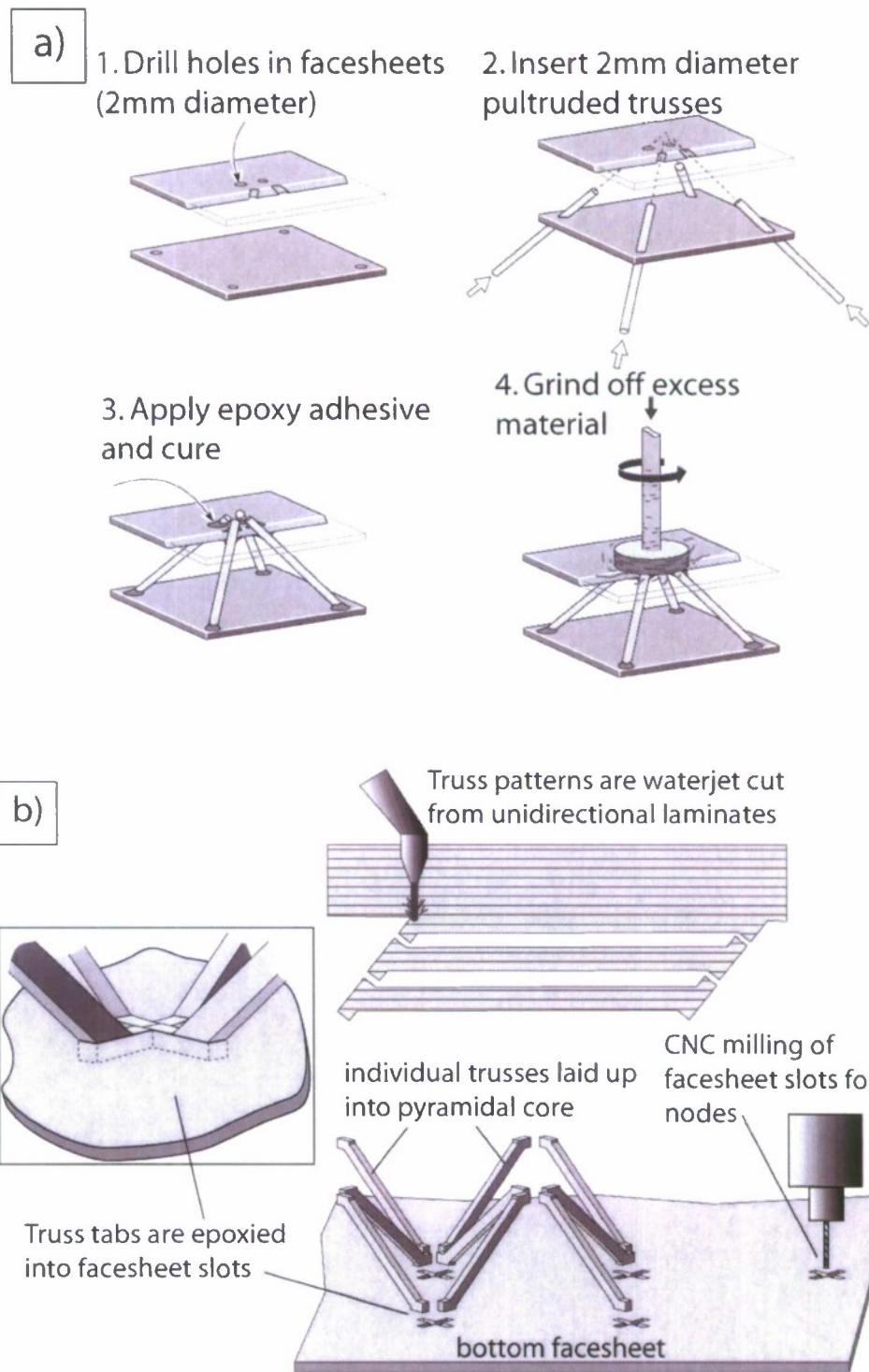
a)

1. Drill holes in facesheets (2mm diameter)

2. Insert 2mm diameter pultruded trusses

3. Apply epoxy adhesive and cure

4. Grind off excess material

b)

Truss patterns are waterjet cut from unidirectional laminates

CNC milling of facesheet slots for nodes

individual trusses laid up into pyramidal core

Truss tabs are epoxied into facesheet slots

bottom facesheet

Fig. 3: Methods for manufacturing CFRP pyramidal cores with uni-directional fiber-reinforced trusses. (a) Pultruded rods truss members are adhesively bonded to face sheets containing pre-drilled holes and excess material removed. (b) Truss patterns are cut from uni-directional laminates and adhesively bonded into milled slots in the face sheets.

A third method for constructing pyramidal cores was employed involving water-jet cutting of pre-fabricated bi-axial CFRP composite laminates. This third manufacturing method, shown in Figure 4, proved to overcome the node failure problem. By using a 0-90° ply lay-up, long snap-fitted truss cut-out patterns are water-jet cut from a single laminate and laid up into a core. Small pockets are milled into the face-sheet in order to mechanically integrate the node into the face-sheet and the whole assembly is epoxy bonded together. While the node strength is increased by using this method, the bi-axial laminate trusses only use 50% of the available fiber in the load bearing truss direction.
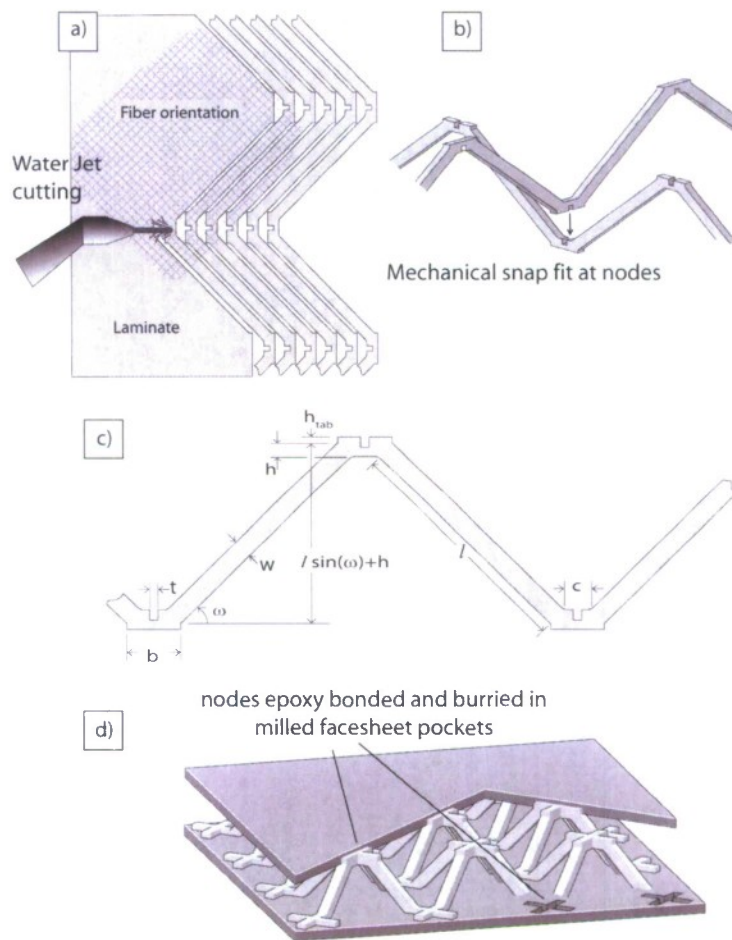

Fig.4: Illustration of the manufacturing route for making the composite pyramidal lattice core sandwich panels studied here. (a) Semi-continuous truss patterns are water jet cut from 0/90° laminate sheets. The fiber directions are shown in this sketch and indicate that a half of the fibers are in the truss axial direction. (b) The pyramidal lattice is assembled by snap-fitting the truss patterns. (c) The geometry of the truss pattern with relevant core design variables identified. (d) A schematic illustration of a pyramidal lattice core sandwich panel. The composite face-sheets utilized cruciform shaped slots into which the pyramidal trusses were fitted and adhesively bonded.
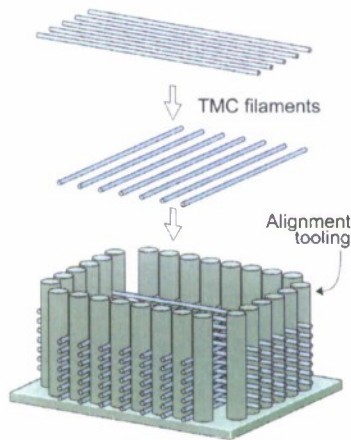
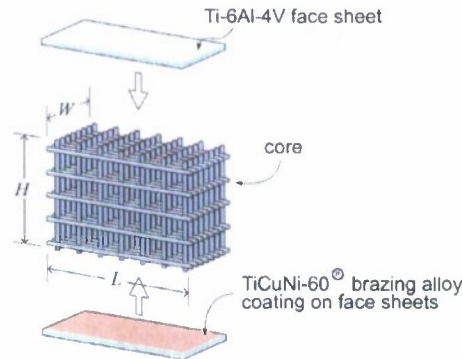## 1. Ti-6Al-4V Pyramidal Lattice Truss Structures

Lattice structure fabrication

A method for fabricating sub-millimeter scale cellular lattice structures with a square/diamond truss topology from 240 µm diameter Ti-6Al-4V coated SiC monofilaments that was developed is summarized here in Fig.5. However, with this diffusion bonding condition (900°C, 4 hours, applied force of 3.75 N per node) the lattice nodes debonded during compression test causing the specimens to fail at relatively low stress. This node debonding was avoided by increasing the diffusion bonding time to 6 hours and the applied force to 8 N per node.
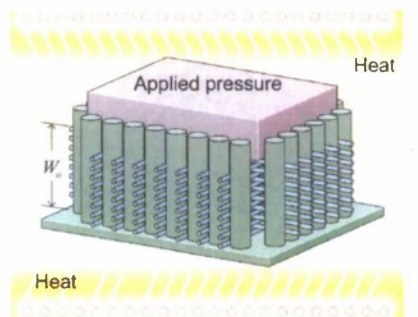
(a) Lattice truss assembly sequence

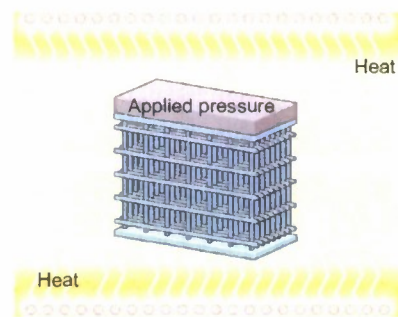(c) Assembly of machined truss core and braze coated face sheets

Ti-6Al-4V face sheet

TMC filaments

Alignment tooling

core

TiCuNi-60® brazing alloy coating on face sheets

(b) Diffusion bonding of truss assembly

(d) Face sheets attachment (brazing)

Heat

Applied pressure

Heat

Applied pressure

Heat

Heat

T = 900° C,   Applied pressure = 1.5-5 MPa,
t = 4 hours,   Background pressure = 10⁻⁷ Torr

T = 975° C,   Applied pressure = 0.01-0.05 MPa,
t = 30 min,   Background pressure = 10⁻⁷ Torr

Fig. 5 Fabrication of a TMC square lattice core sandwich panel: (a) Assembly sequence to make a TMC lattice; (b) vacuum diffusion bonding of the core; (c) sandwich panel lay-up; (d) brazing of face sheets to the square orientated core. A diamond lattice core can be made by rotating the lattice structure by 45° during machining.

Analytical models for the compressive and shear responses of the square and diamond collinear lattice structures
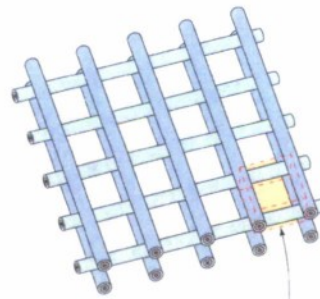
Relative density calculation

Fig. 6 shows a unit cell of the collinear lattice structure prior to and after diffusion bonding process. The relative density of the as layed-up lattice, $\overline{\rho}_o$, is simply the volume fraction of the unit cell occupied by solid truss material:
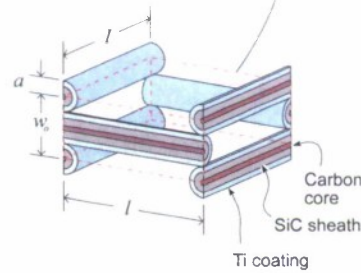
$$\overline{\rho}_o = \frac{V_s}{V_c} = \frac{2\pi a^2 l}{w_o l^2} = \frac{2\pi a^2 l}{4al^2} = \frac{\pi a}{2l} \tag{1}$$

where V_c, V_s, w_o, a and l are the unit cell volume, the volume occupied by the solid truss, the cell width, the filament radius, and the cell length, respectively.

(a) Three layer lattice

(b) As-assembled unit cell

Carbon
core
SiC sheath
Ti coating

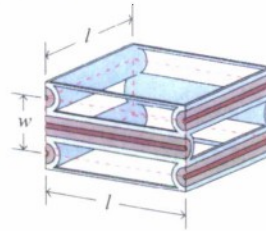(c) Diffusion bonded unit cell

Fig. 6 Representative unit cells of a collinear lattice: (a) three layer lattice; (b) unit cell before diffusion bonding; (c) unit cell of the diffusion bonded structure ($w < w_o$).

During diffusion bonding, the spacing between layers and hence the overall lattice width decreases as the titanium alloy coating at the contact points deforms and interdiffuses. A diffusion bonding coefficient, β, can be introduced as W/W_o where W and W_o are the macroscopic lattice widths prior to and after diffusion bonding process (see Fig. 5 (b) and (c)), respectively. Assuming the titanium alloy coating is redistributed similarly in each collinear layer, β also equals to w/w_o, where w and w_o are the unit cell widths prior to, and after the diffusion bonding process (Fig. 6(b) and (c)), correspondingly. The diffusion bonded unit cell volume can be written as:

$$V_c = wl^2 = \beta w_o l^2 = \beta 4al^2 \qquad (2)$$

Even though the titanium alloy coating is deformed at the contacts, the volume occupied by the solid composite in the unit cell remains the same as in the as layed-up unit cell. The relative density of the diffusion bonded square lattice structure, $\overline{\rho}$, is therefore:

$$\overline{\rho} = \frac{V_s}{V_c} = \frac{2\pi a^2 l}{\beta 4al^2} = \frac{\overline{\rho_o}}{\beta} \qquad (3)$$

For the new diffusion bonding conditions reported above, β is approximately reduced from 0.9 to 0.8.

Micromechanical Analytical models

Square lattice core:

Hutchinson [1] showed that the out-of-plane compressive and transverse shear moduli of the square lattice truss can be expressed as

$$E^* = \frac{1}{2} E_s \overline{\rho}, \qquad (4)$$

and

$$G^* = \frac{1}{16} E_s \left(\overline{\rho}\right)^3, \qquad (5)$$

where E_s and $\overline{\rho}$ are the Young's modulus of the parent material and the relative density of the square core, respective.

Under out-of-plane compression, the square lattices collapse by cooperative Euler buckling of the loaded constituent struts (vertical struts) over the full height of the sandwich core; see Fig.7. If the vertical trusses are not joined together by the horizontal trusses, the buckling stress acting on each vertical truss can be described by the elastic bifurcation stress, σ_c, of a compressively loaded circular column [2,3]:

$$\sigma_c = \frac{\pi^2 k^2 E_s}{4} \left(\frac{a}{l_b}\right)^2, \qquad (6)$$

where E_s is the column elastic modulus, a the column radius and l_b the length of the column between two supporting ends. The factor k depends upon the rotational stiffness of the end nodes with $k = 1$ corresponding to freely rotating pin-joint and $k = 2$ corresponding to built in nodes which cannot rotate [2,3]. For the square lattices, the trusses of length is H (the core height) and we assume $k = 2$. Using this expression for the predicted critical strength of individual truss members, the mechanical properties of the sandwich panel can be globalized since the compressive collapse strength of a core structure, σ_{pk}, can be expressed by [4]:

$$\sigma_{pk} = \Sigma \sigma_c \bar{\rho}, \tag{7}$$

where Σ is a lattice topology dependent scaling factor. The scaling factor $\Sigma = 1/2(sin^2\omega_1 + sin^2\omega_2)$ accounts for the fact that trusses oriented in the loading direction are the most efficient for load bearing, while those that are inclined are limited by force resolution considerations [5,6] For square truss samples half of the trusses have $\omega_1 = 0°$ and another half have $\omega_2 = 90°$ so the effective value of $\Sigma = 0.5$.
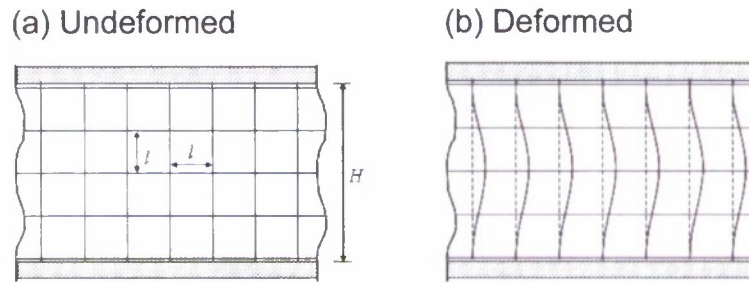
(a) Undeformed   (b) Deformed

Fig. 7 Sketches of: (a) an undeformed square lattice core and; (b) its expected buckling mode under compression.

By substituting Eq. (6) into Eq. (7), the peak compressive strength of a square lattice truss structure failing by elastic buckling is then:

$$\sigma_{pk} = \frac{\pi^2 E_s}{2}\left(\frac{a}{H}\right)^2 \bar{\rho}. \tag{8}$$

Substituting $H = nl$ (where n = numbers of unit cells along the height of the core), Eq.(1) and Eq.(3) into Eq.(8) gives

$$\sigma_{pk} = \frac{2E_s}{n^2\beta}\left(\bar{\rho}_o\right)^3 = \frac{2E_s\beta^2}{n^2}\left(\bar{\rho}\right)^3. \tag{9}$$

However, since the vertical trusses are joined together and hence are forced to buckle cooperatively, an additional shear stress at truss nodes also present [7]. This cooperative buckling mode is similar to the shear buckling mode of a fiber composite material proposed by Rosen [8]. In such model, adjacent fibers buckle in the same wavelength and in phase with one another and the deformation of the matrix material between adjacent fibers is assumed to be primarily a shear deformation. Rosen found that the compressive strength of the fiber composite σ_{cc} due to shear (cooperative) buckling is

$$\sigma_{cc} = \frac{G_m}{1-v_f} + v_f \sigma_{cf},$$ (10)

where G_m, v_f, σ_{cf} are the shear modulus of the matrix, the volumetric fraction of the fibers, and the buckling stress of the fiber, respectively. The first term on the right-hand side of Eq. (10) is the contribution to the composite compressive strength from matrix shear and the remaining term is the contribution to the compressive strength associated with the finite-bending resistance of the fibers. Later on, Fleck [9] argued the matrix shear contribution $G_m/(1-v_f)$, should be replaced by the in-plane shear modulus of the composite when the compressive strength of the composite material is to be estimated.

Using the same analogy, the effective compressive strength of a square lattice controlled by cooperative buckling σ^* is then contributed from resistance to lattice buckling given by Eq. (10) and resistance to lattice shear given by the in-plane shear modulus of the lattice structure, G^*:

$$\sigma^* = G^* + \sigma_{pk}$$ (11)

The peak compressive strength of a square lattice truss structure failing by elastic cooperative buckling becomes:

$$\sigma^* = \left(\frac{1}{16} + \frac{2\beta^2}{n^2} \right) E_s \left(\overline{\rho} \right)^3.$$ (12)

The effective transverse shear strength of the square lattice truss was shown by Hutchinson [1] to be

$$\tau^* = \frac{1}{8} \sigma_c \left(\overline{\rho} \right)^3,$$ (13)

where σ_c is the maximum compressive strength of the constituent trusses set by elastic buckling of the trusses.

Diamond lattice core:

Zupan et al. [10] showed that the out-of-plane compressive modulus of the diamond collinear lattice is given by

$$E^* = \sin^4 \omega \left(1 - \frac{1}{(L/H)\tan\omega} \right) E_s \overline{\rho},$$ (14)

where ω is the angle of inclination between the truss elements and the face sheets, L and H are the length and height of the lattice core, E_s and $\overline{\rho}$ are the Young's modulus of the parent material and the relative density of the diamond core, respective. The transverse shear modulus of the diamond core was developed by Côte et al. [11] in a similar manner and it is given by

$$G^* = \frac{1}{4}\sin^2 2\omega\left(1 - \frac{1}{(L/H)\tan\omega}\right)E_s\bar{\rho}.$$ (15).

The out-of-plane compressive and transverse shear peak strengths are

$$\sigma^* = \sin^2\omega\left(1 - \frac{1}{(L/H)\tan\omega}\right)\sigma_c\bar{\rho},$$ (16)

and

$$\tau^* = \frac{1}{2}\sin 2\omega\left(1 - \frac{1}{(L/H)\tan\omega}\right)\sigma_c\bar{\rho},$$ (17)

respectively, where σ_c is the maximum compressive strength of the constituent trusses. This maximum compressive strength is set by either elastic or plastic buckling of the trusses. Assuming there is no node debonding and the buckling length is governed by the cell size, l buckling between pinned ends, $k = 1$; see Fig. 8 (b), the Euler elastic buckling and Shanley plastic bifurcation stresses are given by [2] ,

$$\sigma_c = \begin{cases} \dfrac{k^2\pi^2 E_s}{4}\left(\dfrac{a}{l}\right)^2 & if\ \dfrac{a}{l} < \sqrt{\dfrac{4\sigma_y}{k^2\pi^2 E_s}}, \\ \dfrac{k^2\pi^2 E_t}{4}\left(\dfrac{a}{l}\right)^2 & otherwise, \end{cases}$$ (18)

respectively. Here, $E_t \equiv d\sigma_s/d\varepsilon_s$ is the tangent modulus of the true tensile stress versus logarithmic strain curve of the parent material evaluated at $\sigma_s = \sigma_c$, and σ_y its yield strength. However if nodes are debonded under compression, the buckling strength would be reduced. The minimum value of this buckling stress is obtained when all the nodes are debonded and the buckling wavelength is governed by the whole length of the trusses, nl when n is the number of unit cells along the truss between two face sheets (see Fig. 8(a) and (c)). The critical buckling stresses can be found by substituting l by nl in Eq.(18)

(a) Undeformed   (b) Deformed (Upper bound)   (c) Deformed (lower bound)
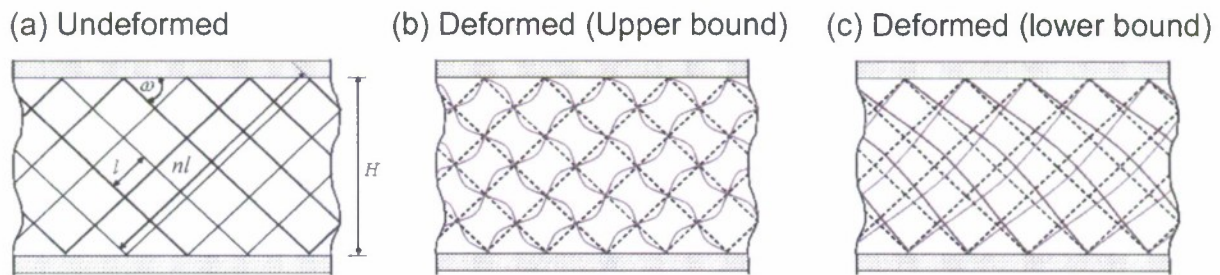

Fig. 8 Sketches of: (a) an undeformed diamond lattice core; (b) expected buckling mode when node failure can be avoided (upper bound); (c) expected buckling mode as subsequence of node failure (lower bound).

Compressive strength/stiffness comparisons with other cellular structures

The highest specific strength lattice structures reported to date have utilized Ti-6Al-4V alloy for the pyramidal truss structure[12]. The specific strength of such lattices was ~ 100 kNm/kg [12]. The specific strength of the titanium composite lattices studied here was 185 kNm/kg. These TMC lattices are therefore the highest specific strength cellular material at ambient temperature reported to date.

The titanium composite lattices investigated here are expected to retain good dimensional stability during compressive loading at temperature below 400 °C (above which creep of the metal component become significant). The compressive stiffness and peak strength of the square TMC lattice structures can be compared with those of similar lattices made from stainless steel and ceramic foams whose service temperatures are all above 400°C in Fig.9. It is evident that TMC square lattice structure, especially with $\bar{\rho}$ = 10.8% and 16.7%, posses higher specific stiffness and strength than any of the other structures/materials. The compressive strengths of the diamond TMC lattices are expected to be significant higher with the new diffusion bonding condition and close to the predicted upper bound values. These materials may therefore provide novel multifunctional opportunities provided the restricted ductility is not a significant constraint.
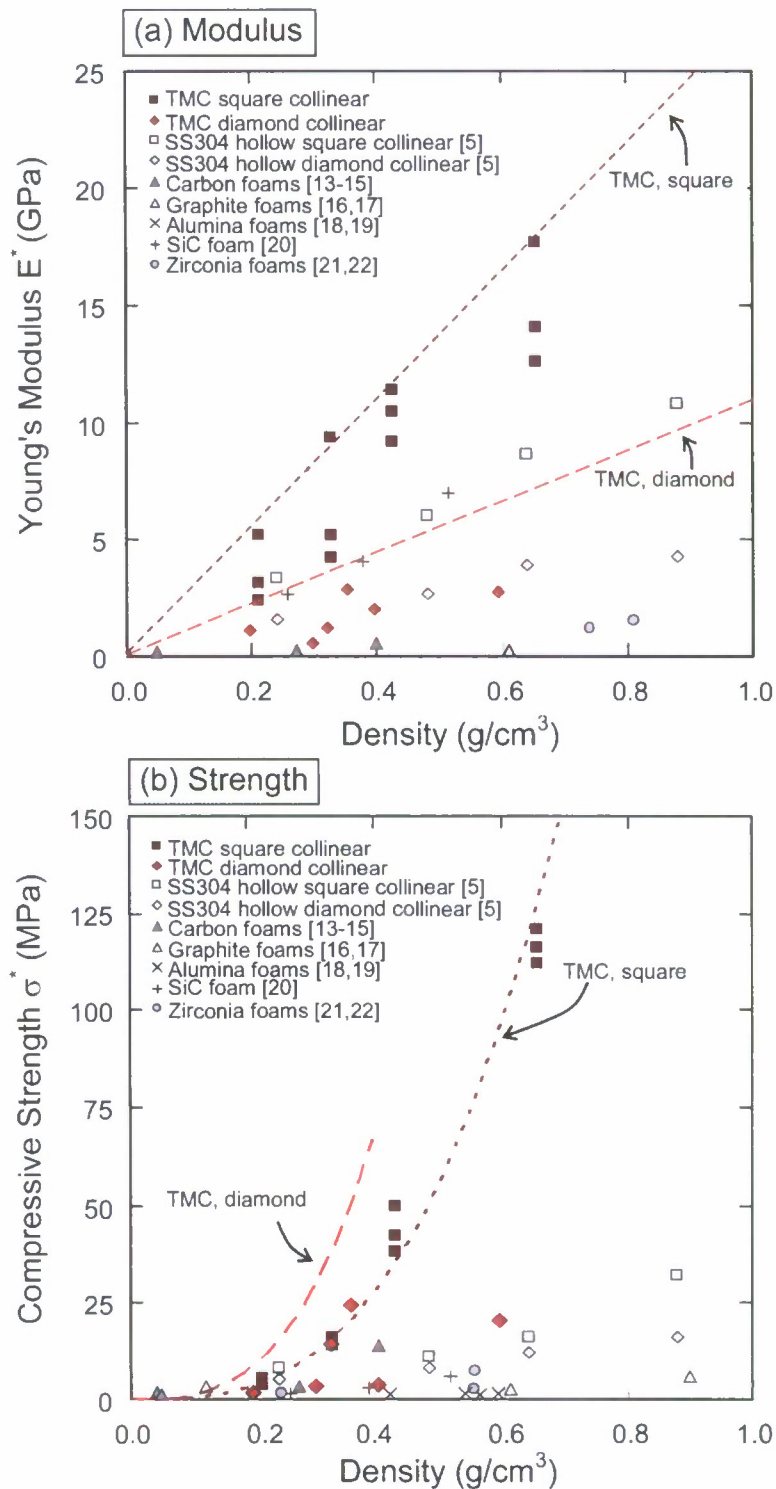
Fig. 9 (a) Stiffness and (b) compressive strength versus density for the TMC and stainless steel collinear square and diamond (upper bound) lattice structures and ceramic foams having service temperature of 400°C and above.

2. Carbon Fiber Composite Pyramidal Structures

In order to investigate the effect of node design on panel strength, two pyramidal cores with different node designs were constructed and tested using the snap-fit manufacturing method described above. Panels were created with a range in relative density from 1-10% with five tests carried out at each relative density. The results of the tests are presented in Figures 10 and 11. Design 1 cores used a small node to minimize the material at the node. Design 2 cores used a larger node to increase the surface area available for connection of the truss to the face-sheet and to reinforce the truss at the interface. The larger nodes in design 2 cores contain some sacrificial material which serves to reinforce the node but does not add to the strength of the core itself. This results in decreased efficiency at higher relative densities.
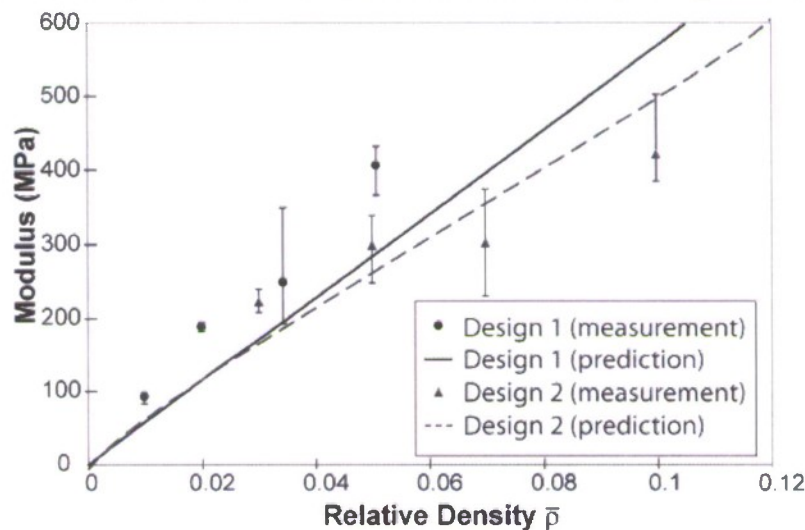

Fig. 10: The measured modulus of core designs 1 and 2. The error bars indicate the maximum and minimum values obtained from five tests. The micromechanical predictions of the modulus for the two designs are also included.

Micromechanical models for panel modulus and peak strength predictions were developed. Modeling of the through-thickness panel modulus for trusses under combined compressive and shear forces (Fig. 10) gives good indications to the general trend in stiffness over a range of relative densities. The model generally under-predicts the measured values at lower relative density. It is suspected that the under-prediction stems from errors in the measured value of the laminate modulus as small misalignments in the experimental setup can cause large deviations in the measured value of material properties. The effect of the sacrificial node material in design 2 decreases the modulus with increasing relative density as can be seen in Figure 10.

Strength models based on different failure mechanisms (Figure 11) give excellent correlation to the measured peak strength values. The analysis also indicates the regions where different failure modes are active. At low relative densities elastic buckling is active. Failure transitions to a delamination mode at approximately 2% relative density. This transition corresponds to the most weight efficient design. At higher relative densities, plastic microbuckling is predicted to be the dominant failure mode. The downward curve of the plastic microbuckling strength prediction in Figure 11b gives a maximum panel strength limit. The same peak also occurs for Design 1 but is outside the range of the graph in Figure 11a.

The analysis reveals the most weight efficient designs as well as predicts the maximum strength attainable using the snap-fitted truss manufacturing process (Figure 4). A log-log plot of available engineering materials (Figure 12) shows that at low densities, these pyramidal CFRP lattice structures out-perform other available light-weight panels. At higher densities, they are competitive with light-weight metal alloys such as aluminum. Figure 12 also presents the theoretical limit for CFRP lattice structures if premature node failure and delamination failure mechanisms can be overcome. Literature suggests that different fiber-matrix systems and fiber configurations, such as braiding, may defeat or delay delamination. Further design iterations may also solve the node failure issues in unidirectional truss cores.
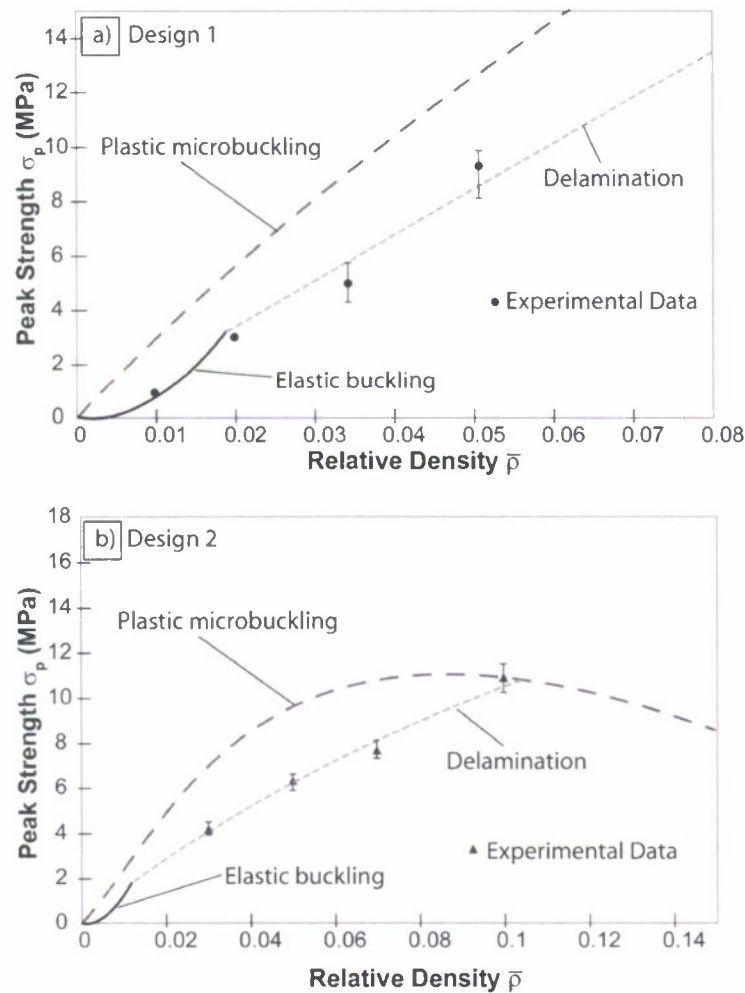

Fig. 11: The measured peak strength of (a) design 1 and (b) design 2 of the composite pyramidal cores. The error bars indicate the maximum and minimum values obtained from the five tests. The predictions of the strength for the two designs are also included based on the Euler buckling, inter-ply delamination and micro-buckling failure modes of the struts.
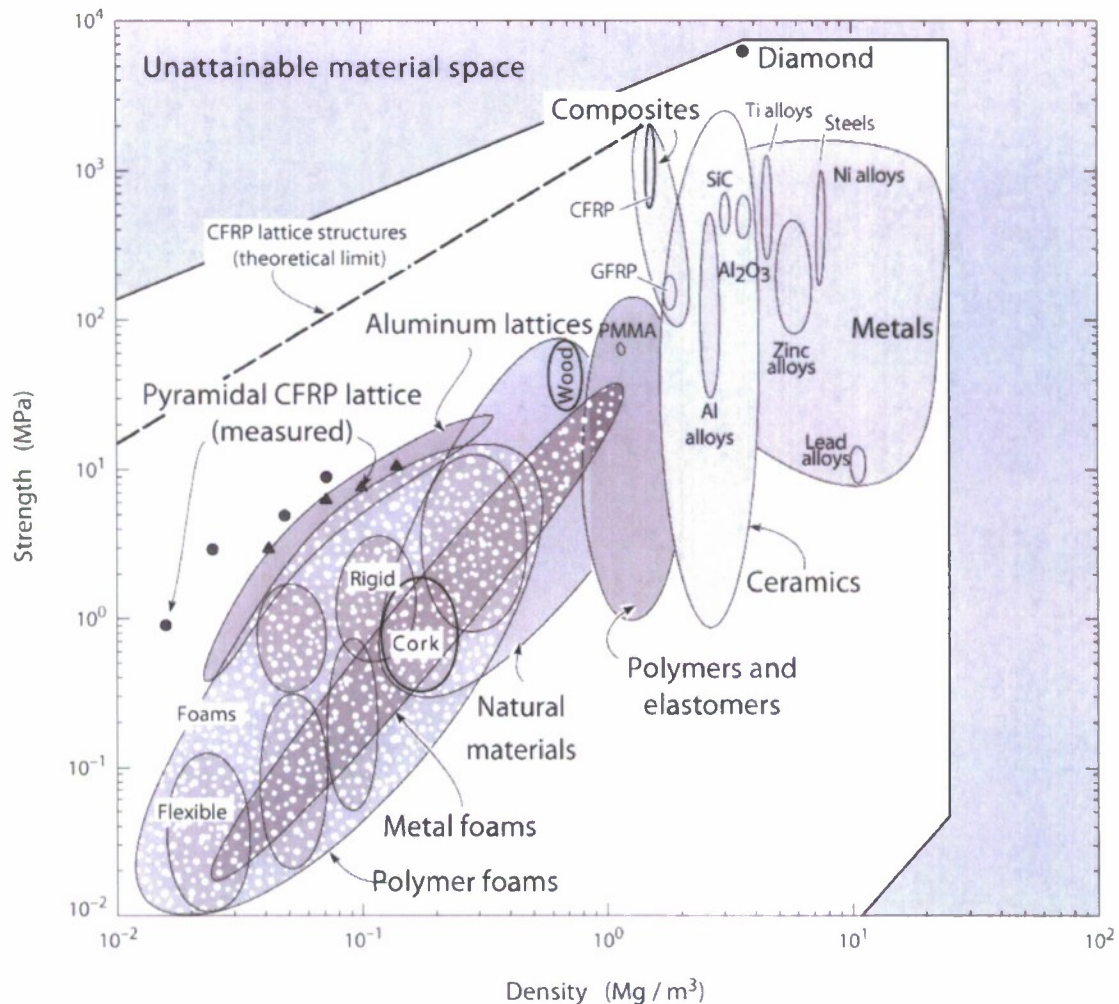
Fig. 12: An Ashby material strength versus density property space map for engineering materials contains gaps between existing and unattainable materials. The maximum theoretical strength of composite lattice structures is shown by a dashed line. The measured properties of the composite pyramidal lattice materials investigated in our research are also shown.

References

[1] Hutchinson RG. Mechanics of lattice materials. PhD thesis. Cambridge University. Department of Engineering. 2004.

[2] Shanley FR. Mechanics of materials. New York: McGram-Hill; 1967.

[3] Gere JM, Timoshenko SP. Mechanics of materials. Boston: PWS Engineering; 1984.

[4] Wadley HNG, Fleck NA, Evans AG. Compos Sci Technol 2003;63:2331.

[5] Queheillalt DT, Wadley HNG. Acta Mater 2005;53:303.

[6] McCormick TM, Miller R, Kesler O, Gibson LJ. Int J Solid Struct 2001;38:4901.

[7] Vayas I, Ermopoulos J, Pasternak H. J Construct Steel Research 1995;35:165.

[8] Rosen BW. in Fiber composite materials. American Society of Metals;1965. pp.37-75.

[9] Fleck NA. Adv Appl Mech 1997;33:43.

[10] Zupan M, Deshpande VS, Fleck NA. Euro J Mech A Solid 2004;23:411.

[11] Côté F, Deshpande VS, Fleck NA, Evans AG. Int J Solid Struct 2006;43:6220.

[12] Queheillalt DT, Wadley HNG. Submitted to Mater Design, Sept 2006.

Appendices

[A]. Paper on "Fabrication and structural performance of periodic cellular metal sandwich structures" H.N.G. Wadley, N.A. Fleck and A.G. Evans., Composites Science and Technology 63(2003) 2331-2343.

[B]. Paper on "Structural performance of metallic sandwich beams with hollow truss cores," H.J. Rathbun, F.W. Zok, S.A. Waltner, C. Mercer, A.G. Evans, D.G. Queheillalt, and H.N.G. Wadley, Acta Materialia 54 (2006) 5509-5518.

[C]. Paper on "Compressive behavior of age hardenable tetrahedral lattice truss structures made from aluminium," G.W. Kooistra, V.S. Deshpande and H.N.G. Wadley, Acta Materialia 52(2004) 4229-4237.
[D]. Paper on "Lattice truss structures from expanded metal sheet," G.W. Kooistra and H.N.G. Wadley, Materials and Design 28(2007) 507-514.

[E]. Paper on "Hierarchical Corrugated Core Sandwich Panel Concepts," G.W. Kooistra, V. Deshpande, and H.N.G. Wadley, Journal of Applied Mechanics 74 (2007) 259-268.

[F]. Paper on "Pyramidal lattice truss structures with hollow trusses," D.T. Queheillalt and H.N.G. Wadley, Materials Science and Engineering A 397(2005) 132-137.

[G]. Paper on "Thermal Applications of Cellular Lattice Structures," H.N.G. Wadley and D.T. Queheillalt, Materials Science Forum, 539(2007), pp. 242-247.

[H]. Paper on "Truss Waviness Effects in Cellular Lattice Structures," D.T. Queheillalt, V. S. Deshpande and H.N.G. Wadley, Journal of Mechanics of Materials and Structures, Vol. 2, No. 9, 2007, pp.1657-1675.

[I]. Paper on "Mechanical properties of an extruded pyramidal lattice truss sandwich structure," D.T. Queheillalt, Y. Murty, and H.N.G. Wadley, Scripta Materialia 58(2008) 76-79.

[J]. Paper on "Shear behavior of aluminum lattice truss sandwich panel structures," G.W. Kooistra, D.T. Queheillalt, H.N.G. Wadley, Materials Science and Engineering A 472(2008)242-250.

[K]. Paper on "The Compressive response of carbon fiber composite pyramidal truss sandwich cores," K.Finnegan, G. Kooistra, H.N.G. Wadley and V.S. Deshpande, Int. J. Mat. Res. 98(2007) 12.

[L}. Paper on "Titanium matrix composite lattice structures," P.Moongkhamklang, D.M. Elzey, and H.N.G. Wadley, Composites: Part A 39(2008) 176-187.

[M]. Paper on "Experiment assessment of the ballistic response of composite pyramidal lattice truss structures," C.J. Yungwirth, D.D. Radford, M. Aronson, H.N.G. Wadley, Composites: Part B 39(2008) 556-569.

[N]. Paper on "Impact response of sandwich plates with a pyramidal lattice core," C.J. Yungwirth, H.N.G. Wadley, J.H. O'Connon, A. J. Zakraysek, and V.S. Deshpande, International Journal of Impact Engineering 35 (2008) 920-936.